

## **Coastal and Submesoscale Process Studies for ASIRI**

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### **LONG-TERM GOALS**

Our over-arching objective is to gain an understanding of upper ocean processes and air-sea interaction in the Bay of Bengal. This, in the long run, would contribute toward improving the intra-seasonal Monsoonal forecast in ocean-atmosphere coupled models. Several specific goals are listed below.

1. To determine the upper ocean structure of temperature and salinity at different times of year, and to understand its relationship with air-sea fluxes of heat and moisture in the Bay of Bengal.
2. To determine what processes control the surface temperature, the mixed layer depth, and the density stratification in the Bay.
3. To examine the influence of surface freshwater on the stratification, submesoscale dynamics, and mixing.
4. To examine the mechanisms by which the surface freshwater is dispersed.
5. To determine how one-dimensional and three-dimensional mixing and advective processes in the upper ocean influence the upper ocean temperature and air-sea fluxes.
6. Develop and foster collaboration with Indian scientists through ASIRI-OMM and offer training and educational opportunities as part of this collaboration.

### **OBJECTIVES**

More specific objectives are:

1. Conduct modeling process studies to examine and evaluate lateral and vertical routes for dispersal of the freshwater in the Bay of Bengal.

2. Organize and participate in research cruises in the Bay of Bengal for gathering data along with other ASIRI PIs
3. Analyze data sets from the cruises in collaboration with ASIRI-OMM members.
4. Provide shore support for ASIRI and OMM cruises. Enable partnership with our international partners.
5. Train students on research cruises, work with them on analysis of data and modeling.

## APPROACH

We conducted several numerical process experiments before the ASIRI –OMM cruises on the US R/V Roger Revelle and Indian R/V Sagar Nidhi. In Nov-Dec 2013, June-July 2014 and August-Sept 2014 we also provided shore support guidance for field measurements. PIs contributed to planning of the August-Sept 2015 R/V Revelle cruise from Chennai, India, and in obtaining permissions for the port call in India. In addition to the PIs the key individuals on the following activities are:

Dr. Sanjiv Ramachandran (Research Associate, UMass Dartmouth), Jared Buckley (Graduate Student, UMass Dartmouth), Dr. Melissa Omand (Postdoctoral Investigator at WHOI until 12/14, and continued to work on a subcontract to URI in Jul-Aug 2015).

The following activities were undertaken this year. Many of these were conducted in collaboration with other ASIRI investigators, particularly (ii) in collaboration with Andrew Lucas, Rob Pinkel (Wirewalker data), Jonathan Nash and Jen Mackinnon (ADCP data) Bob Weller and Tom Farrar (uCTD data and air-sea fluxes), and the chief scientists (Emily Shroyer and Amala Mahadevan) for Leg-2.

1. Analysis of the data collected during the November and December 2013 cruise: Testing Geostrophy
  - Analysis of PV structure
  - Analysis of temperature-salinity variability along uCTD sections from Leg 2
  - Examining apparent optical properties of water
  - Large-scale distribution of oxygen, nitrate and density
2. Exploratory simulations to guide the August 2014 cruise (on R/V Nidhi), and August-September 2015 cruise on Revelle.
3. Enabling the Chennai Revelle 2015 port call by working closely with many stakeholders in the USA and in India.
4. Participating in the 2015 cruise on the Revelle. Mahadevan and Tandon are both on the cruise with their graduate students. Amit Tandon is co-chief scientist with Jonathan Nash.

## RESULTS

- (i) Analysis of data collected during the November 2013 and December 2013 cruises: At what scales is geostrophy valid?: We extended our earlier analysis of submesoscale instabilities for the

process study at 16N during leg 1 (CBPS for Central Bay Process Study) to include two high-resolution UCTD process studies conducted during leg 2, referred to hereafter as the Southern Bay Process Study (SBPS, at 8N) and Northern Bay Process Study (NBPS, at 17N). By contrasting the results from the three process studies we showed the presence of submesoscales in the Bay of Bengal depends crucially on the relative orientation of the winds and the lateral buoyancy gradient. Prior to our analysis, we detided the density and velocity fields using plane-wave solutions for the M2 tide, obtained from measurements of velocity and density by the Wirewalker (analysis by Drew Lucas and Rob Pinkel). An analysis of the density and velocity fields for geostrophy at scales of 8km reveals it is approximately satisfied for CBPS (Fig. 1) but not for the other two. There are also interesting differences between the For CBPS, where the winds were downfront, the velocity and density fields show several signatures that suggest an active submesoscale field. Some of these include negative potential vorticity, frontal subduction,  $O(f)$  relative vorticities and a positive skewness of the vorticity field (Fig. 2), the last of which is consistent with the dominance of the submesoscale signal over that due to internal waves. In contrast, NBPS was characterized by upfront winds and none of the submesoscale signatures mentioned above. The process study SBPS witnessed both upfront and downfront winds, deeper mixed layers but very few of the submesoscale signatures seen in CBPS, perhaps due to the weaker lateral gradients in density. Ongoing work using simulations initialized with sections from the three process studies is currently underway. We will use the results from these simulations to gain additional insights on the physics distinguishing these three process studies.

- (ii) Analysis of data collected during the November 2013 and December 2013 cruises: Potential Vorticity: Figure 2 shows a UCTD radiator survey conducted in a region of strong frontal gradients (after a storm) forced by weak wind stresses ( $O(0.01N/m^2)$ ). During this survey we measured horizontal buoyancy gradients as large as  $O(10^{-6}m/s^2)$ , confined to shallow  $O(10m)$  mixed layers. The radiator survey presents an illustrative contrast to previous studies that have extensively documented the presence of submesoscale instabilities for deeper ( $O(100m)$ ) mixed layers. The observed conditions present a unique opportunity to examine whether submesoscale instabilities can even occur for such shallow mixed layers. One of the signatures for submesoscale instabilities is negative values in the potential vorticity field, which implies conditions favorable to the onset of symmetric instability (SI). Before obtaining the potential vorticity field for SI in the Bay of Bengal, we de-tided the density and velocity signal (Figure 3) using the tidal solution provided by Andrew Lucas and Rob Pinkel from their analysis of the Wirewalker data. With the de-tided density and velocity we then calculated the different contributions to the potential vorticity field. In Figure 4 we show the results of this calculation using the velocity data from the sentinel mounted on the side of the ship. Both lateral density gradients and the vorticity field give rise to patches of negative potential vorticity, which are  $O(10m)$  thick and  $O(1-5km)$  wide. Further analysis (plot now shown) suggests the 8-km smoothed density and velocity fields meet the necessary condition for SI (Thomas *et al.* 2013). We are currently exploring the generation of negative PV during the radiator survey using submesoscale-resolving three-dimensional numerical simulations, initialized with temperature-salinity sections from the survey.
- (iii) Analysis of 2013 cruise data --Salinity and temperature: We found that the density of the upper 50 m is strongly dictated by salinity. We see very strong vertical density stratification due to freshwater that enters the Bay from the Ganges, Brahmaputra and Irrawaddy rivers, post monsoon. Subsurface temperature maxima exist and often a second layer of thermal stratification is seen deeper. The freshwater lies almost entirely in the upper 50 m and the freshwater content increases toward the North where the largest riverine discharge occurs. Irrawaddy water was distinguishable from Ganges-Brahmaputra water and was seen at the northernmost region of our

survey, as well as in an intra-thermocline eddy that was sampled. Mesoscale eddies play a significant role in transporting the freshwater.

- (iv) Analysis of 2013 cruise data –Frontal gradients: We find the lateral density gradients in the surface mixed layer to be controlled almost entirely by salinity. Fronts are seen over a range of scales – from hundreds of meters to tens of kilometers, which the strongest gradients at submesoscales. Temperature is more or less passive, but shows some correlation with salinity, but we see no temperature compensation, except at the smallest scales. Process modeling was conducted to better understand these temperature variations, which occur due to negative air-sea heat fluxes that cool the shallow, freshwater stratified regions on one side of the front to a greater extent than the deeper mixed layers on the other side.
- (v) One-dimensional modeling: The PWP model was run on T,s profiles that show a strong barrier layer in the northern Bay of Bengal. With cooling, convection occurs at first in the upper fresh mixed layer, but is inhibited from breaking in to the barrier layer. Only when the temperature falls below a threshold does it penetrate in to the barrier layer, and then proceed quickly to the bottom of the barrier layer. This modeling demonstrated the mechanism by which vertical mixing can break through the barrier layer.
- (vi) Restratification of the mixed layer: Our model simulations show that several mechanisms contribute to the strong stratification: a) freshwater input, b) mixed layer eddies – which redistribute the freshwater at the surface and convert horizontal density gradients into stratification, and c) Ekman transport, which can move freshwater over the denser side of the front. These mechanisms are seen to contribute to different extents, depending on the region.
- (vii) Exploratory simulations to guide the August-September 2015 cruise (on the Nidhi): We performed some idealized submesoscale-resolving simulations with the K-profile parameterization (Large et al., 1994) to simulate the fate of a freshwater lens under conditions typical of the northern Bay during the summer monsoon. The simulations illustrate the effects of “upfront winds,” that result in the advection of lighter over denser water, on the stratification of the upper water column. We initialize the simulations with T-S profiles from a rapidly profiling Argo float near 18N in August 2013. We force these profiles with 6-hourly winds and surface heat fluxes from the MERRA reanalysis product for August 2013. To create the freshwater lens we subject the model to a single pulse of rainfall at the rate of 80mm/hr for one inertial period (39 hours). The rainfall occurs only within a 100km band ( $y=220-320\text{km}$ ), halfway between the meridional boundaries. Figure 3 shows the temporal evolution of the vertical stratification ( $N^2$ ) at three “virtual moorings” which provide an Eulerian time series of density (among other variables). To study the effects of freshwater, the three moorings are chosen to lie: (i) north of the precipitation band; (ii) within the precipitation band; and (iii) south of the precipitation band. The variation of  $N^2$  is markedly different at the northernmost mooring and the other two. At the former,  $N^2$  has a persistent maxima between 20-30m and a shallower maxima near the surface driven by the diurnal cycle. In contrast, the locations of the maxima at the model moorings inside and to the south of the rain band (see regions marked by ovals in Fig. 3) are qualitatively similar to those seen in observations from real moorings in the Bay at 18N. This hints at a role for lateral density gradients in setting the vertical stratification, which we are exploring further through additional simulations.
- (viii) International Partnership Development: Tandon worked on enabling the *Revelle* port call, and the travel logistics (FRRO process) for the US science team by working closely with all the stakeholders, in both USA and India. This entailed coordination with the US State Department,

Indian Embassy in Washington DC, the Ministry of Earth Sciences New Delhi, Indian OMM collaborating PIs and various other ministries and stakeholders.

## PUBLICATIONS

Wijesekara, H. and 20 co-authors, Decrypting a mystery bay: ASIRI ocean-atmosphere initiative in the Bay of Bengal. *Submitted to BAMS*

Sudip Majumder, Amit Tandon, Daniel L. Rudnick, and J. Thomas Farrar. Near-inertial kinetic energy budget of the mixed layer and shear evolution in the transition layer in the Arabian Sea during the monsoons. (*J. Geophys. Res. Oceans, In Press*, <http://dx.doi.org/10.1002/2014JC010198>)

Ramachandran, S., A. Tandon and A. Mahadevan, Enhancement in vertical fluxes at a front by mesoscale-submesoscale coupling, 2014, *J. Geophys. Res.* 119 (12), 8495-8511, doi: 10.1002/2014JC010211

Nagai, T. A. Tandon, E. Kunze and A. Mahadevan, Spontaneous generation of near-inertial waves by the Kuroshio front, 2015, *J. Phys. Oceanogr.* 45, 2381-2406. doi: [10.1175/JPO-D-14-0086.1](https://doi.org/10.1175/JPO-D-14-0086.1)

### **Manuscripts in preparation**

Upper ocean structure and variability in the Bay of Bengal

Shroyer, E., A. Gordon, M.M. Omand, G-S. Jaeger, M. Freilich, R. Weller, J.T. Farrar, A. Mahadevan

Penetrative Heat Flux in the Bay of Bengal

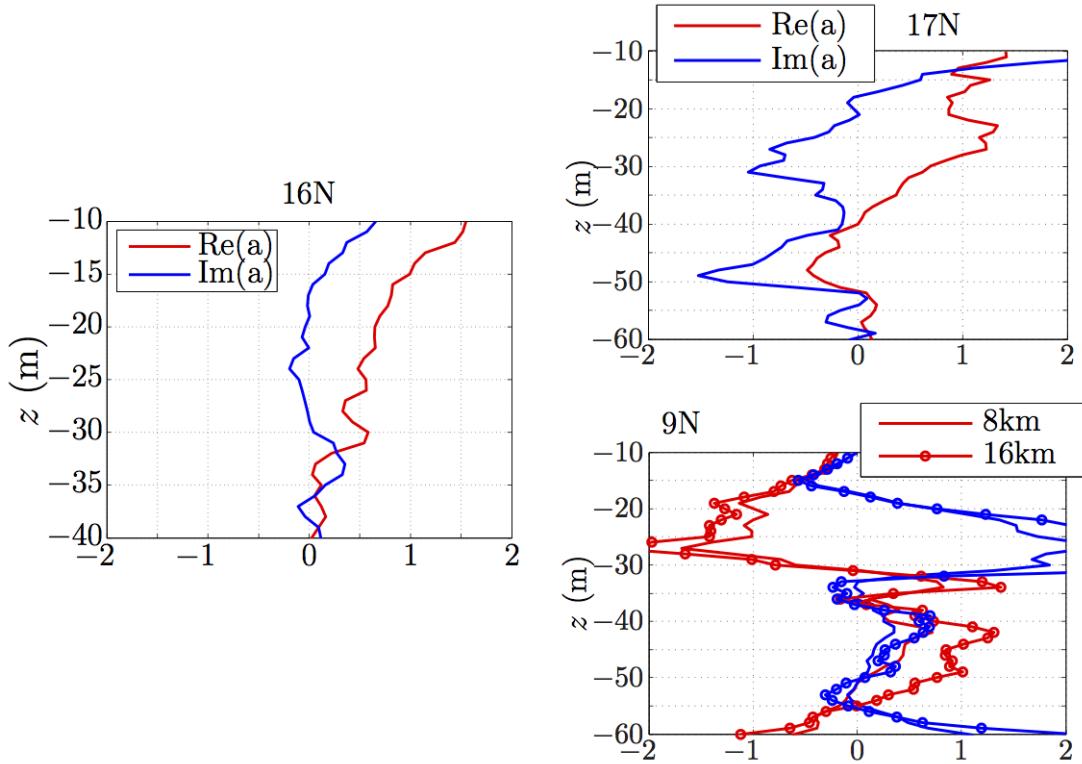
Aneesh A. Lotliker, Melissa M. Omand, Andrew J. Lucas, Samuel R. Laney and M. Ravichandran

Collapse of the 'barrier layer' in the Bay of Bengal

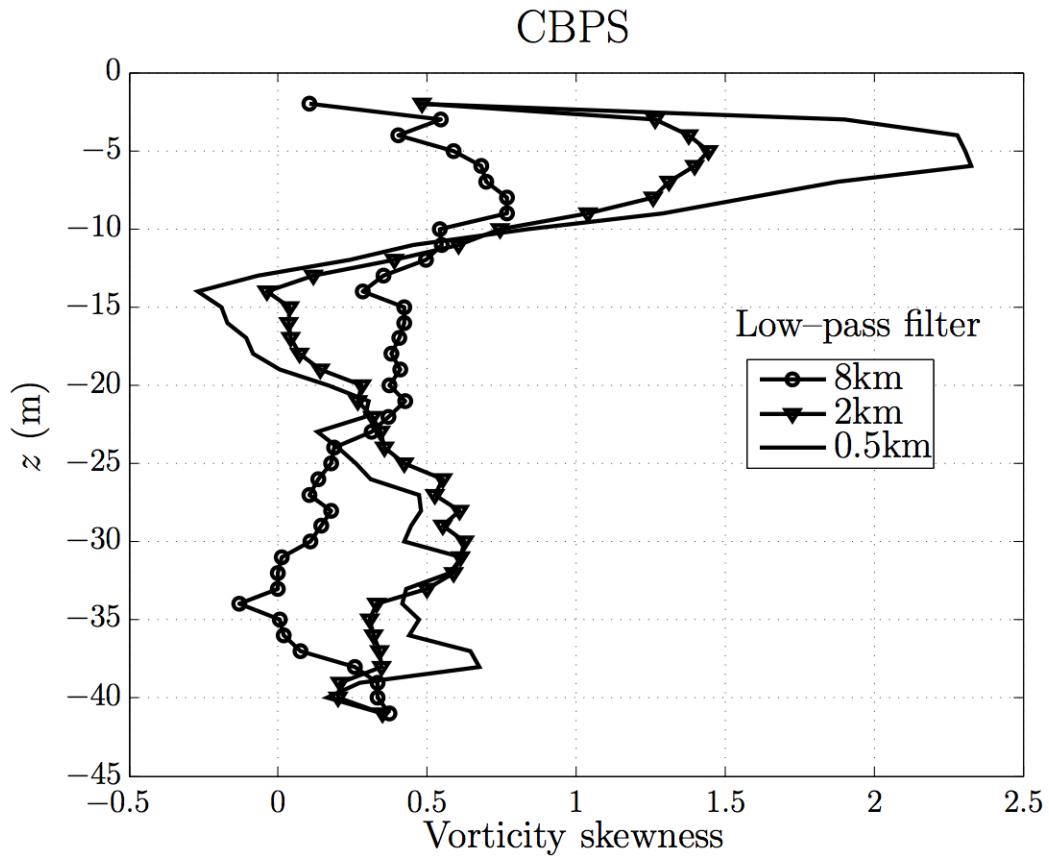
Melissa M. Omand, Amala Mahadevan, Joseph E. Salisbury, Samuel R. Laney, Emily L. Shroyer, Andrew J. Lucas, Robert A. Weller, J. Tom Farrar

Submesoscale stirring in shallow, stratified layers in the Bay of Bengal: Observations during the winter Monsoon. Sanjiv Ramachandran, Amit Tandon, Jennifer Mackinnon, Amy Waterhouse, Andrew Lucas, Robert Pinkel, Jonathan Nash, Emily Shroyer, Amala Mahadevan, Robert Weller and Tom Farrar

Interaction between submesoscale lateral gradients and winds in shallow mixed layers during the summer monsoon: numerical studies in the Bay of Bengal. Sanjiv Ramachandran, Amit Tandon

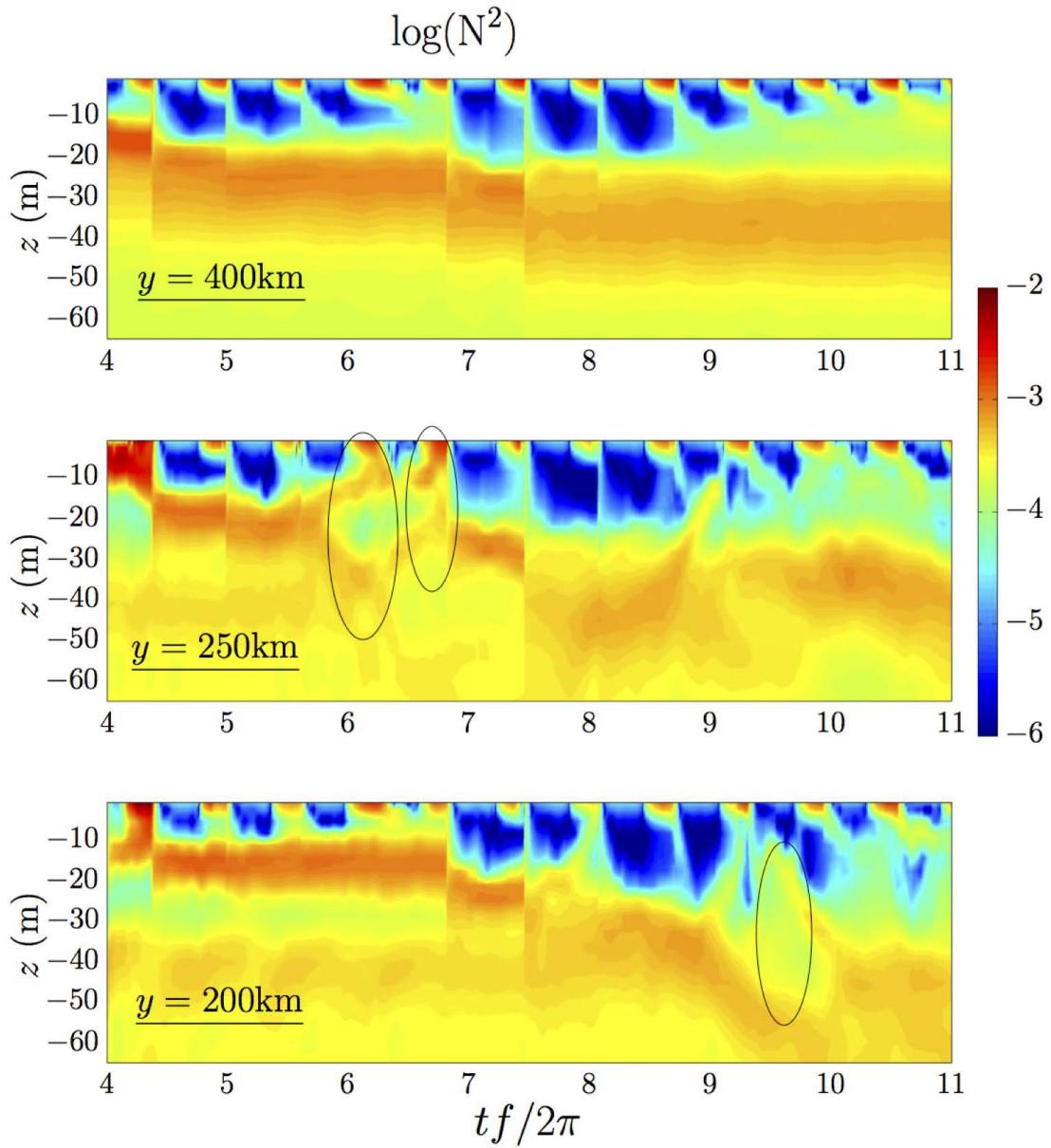


**Figure 1: Real and imaginary parts of  $a$ , the correlation coefficient between the complex shear vector and the complex lateral buoyancy gradient. A value of  $a=1+0i$  implies perfect geostrophy. Inherent noise in the signal can reduce the magnitude of  $a$  without changing its phase. Hence, a near-real value of  $a$  (i.e., small imaginary part) with a magnitude smaller than 1 suggests geostrophy (Rudnick and Luyten, 1995).**

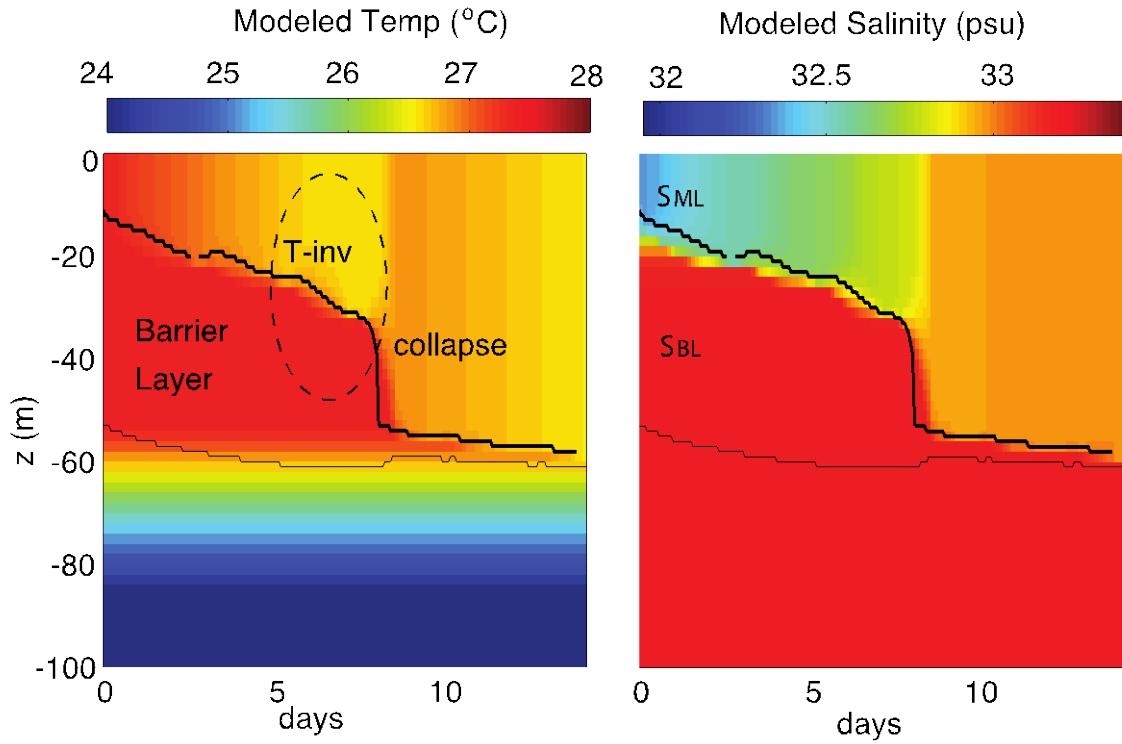


**Figure 2:** Skewness of the vorticity field smoothed over different spatial scales. A velocity field where the lateral variability is predominantly due to internal waves will exhibit zero skewness.

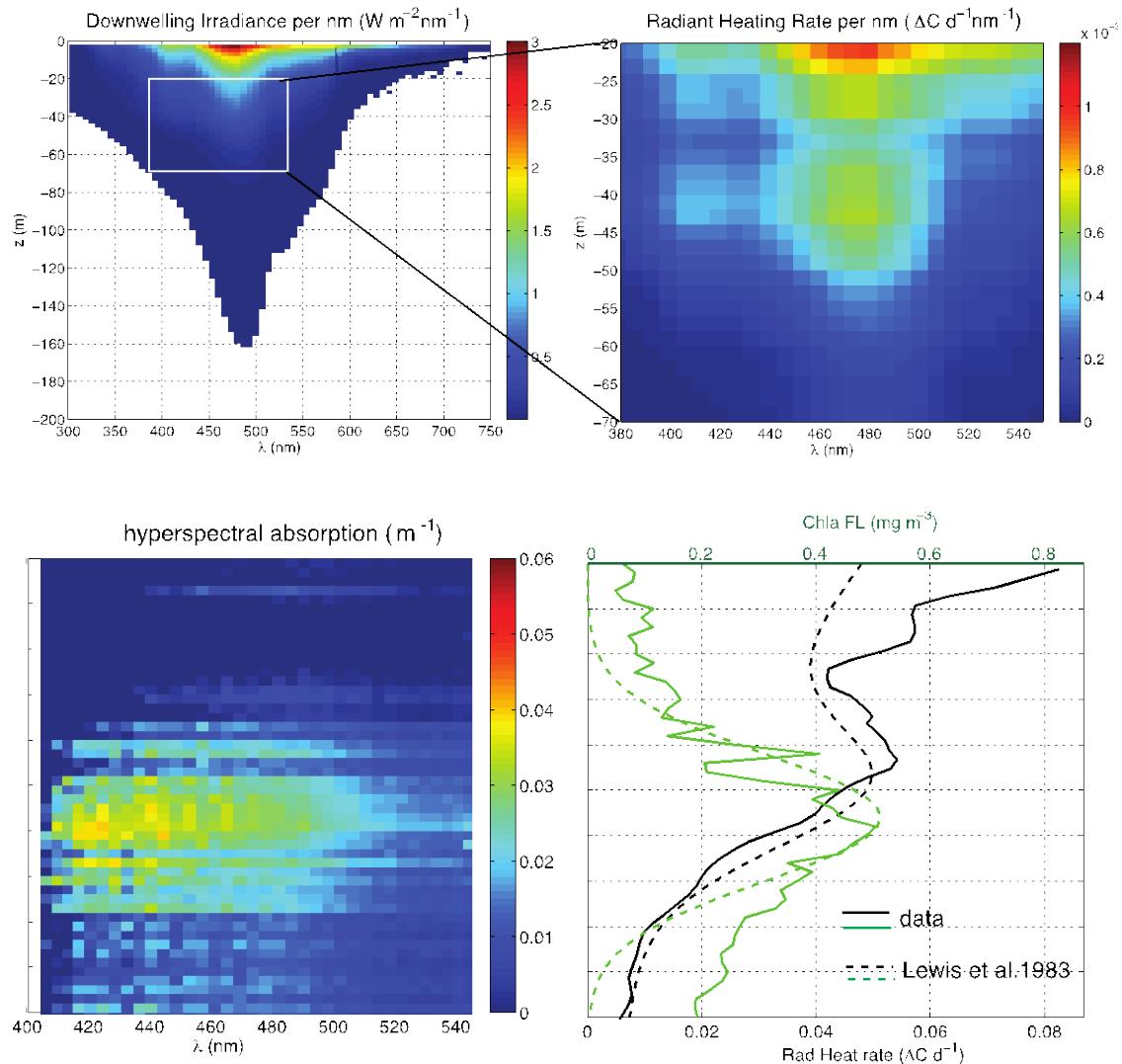
A positive value of the skewness argues against this possibility and suggests an energetic submesoscale field, consistent with earlier submesoscale-resolving simulations and observations of mixed-layer fronts.



**Figure 3:** Evolution of vertical stratification at three “virtual moorings” located north of the rain band ( $y=400\text{km}$ ), within the rain band ( $y=250\text{km}$ ) and to the south of the rain band ( $y=200\text{km}$ ). The precipitation occurs within a zone spanning 220-320km. The regions marked by ovals show a double peak in the stratification, similar to observations from real moorings in the Bay at 18N. This structure is present only in the moorings inside and to the south of the rain band.



**Figure 4:** PWP simulations of a) Temp and b) Salinity over 14 days. The model was initialized with an idealized profile that was based on the observed UCTD profiles from the Northern Bay of Bengal where the barrier layer was strongest. The model was forced by the observed negative net heat flux. After roughly 8 days, the fresh surface mixed layer has cooled, and the density roughly matches the density within the barrier layer. At this time we observe an abrupt collapse as the mixed layer and the barrier layer merge.



**Figure 5:** An example profile of a) hyperspectral irradiance  $Id$ , b) radiant heating rate  $RHR$  (estimated from  $d Id/dz$ ), c) hyperspectral absorption a, d) net  $RHR$  (black) and  $Chl FL$  (green) from the IOP package deployed during ASIRI CTD casts in 2013. In d), dashed lines show the Lewis et al. (1983) model for comparison.